The inner environment of protoplanetary disks with near infrared spectro-interferometry

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Abstract. In this paper, I review how optical spectro-interferometry has become a particularly well suited technique to study the close environment of young stars, by spatially resolving both their IR continuum and line emission regions. I summarize in which ways optical interferometers have brought major insights about our understanding of the inner part of circumstellar disks, a region in which the first stages of planet formation are thought to occur. In particular, I emphasize how new methods are now enabling to probe the hot gas emission, in addition to the circumstellar dust.

Keywords: interferometry – star and planet formation – protoplanetary disks – near infrared excess – emission lines
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INTRODUCTION

Observing the protoplanetary disks around young stars is a key issue to understand the first steps of planet formation mechanisms. Such processes are occurring in the very inner environment of the central star, at distances of a few Astronomical Units. The representation that we have today of this environment is sketched in Fig. 1, and is basically composed of i) magnetically-driven columns of gas accreting on the central star, ii) a gaseous dust-free rotating disk, iii) a dusty disk which inner rim is located at the dust sublimation radius; and iv) potentially outflowing winds. Observational clues that we can obtain of the inner part of the protoplanetary disks are twofold:
From their continuum infrared excess, that arises from the emission of the hot circumstellar dust and gas. It will give information about the structure/geometry of the disk as well as about its composition (e.g. grain growth, radial/vertical distribution, mineralogy);
From their infrared emission lines, in particular the hydrogen lines, that can originate from mainly two different mechanisms: whether magnetospheric accretion along the accreting columns of gas [1] or through magnetically-driven outflows [2, 3, 4].
In order to characterize these mechanisms unambiguously, one needs both spatial and spectral resolution to localize and separate the continuum and line emission regions. At distances of the first stellar formation regions ($\sim$ 150pc), 1AU corresponds to a angular distance of $\sim$ 6mas, a resolution that only interferometric techniques can achieve. Furthermore, at such distances from the star, the temperature at the inner region of young stars is roughly between a few 100K and a few 1000K, that is radiating at near infrared wavelengths. As a result, near infrared spectro-interferometry which provides both the spatial and spectral resolution required at the desired wavelengths appears to be a technique perfectly suited to observe the inner environment of protoplanetary disks.

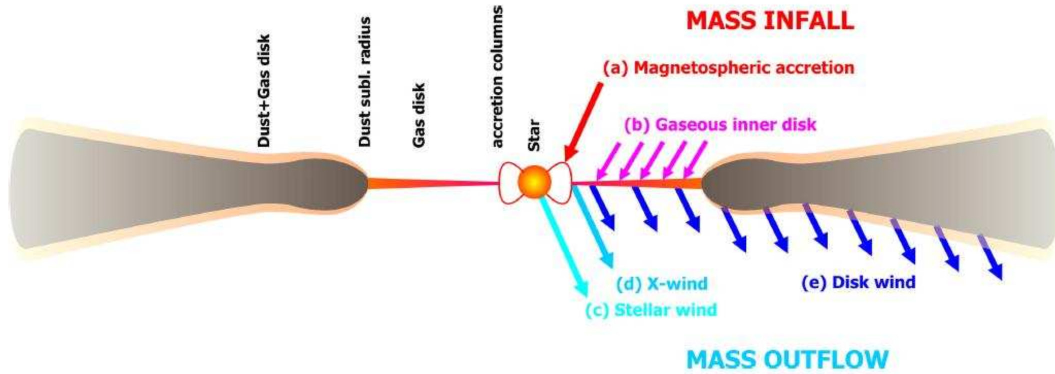

FIGURE 1. Sketch of the inner environment around young stellar objects, from [5]. See text for detailed description.

ORIGIN OF THE NEAR INFRARED EXCESS: THE K-BAND SIZE-LUMINOSITY RELATIONSHIP

By observing young stars at near infrared wavelengths, interferometry has enabled to *locate* the emission region responsible for the continuum infrared excess, and potentially constraint its structure. And such dimensional constraints appeared to be critical to unveil the physical origin of this emission, both for low (T Tauri) and intermediate (Herbig Ae/Be) mass young stars.

Herbig Ae/Be stars: thermal emission of the dusty inner rim

Monnier et al. [6], Vinković and Jurkić [7] have shown on a sample of Herbig Ae/Be stars that the interferometric size of the K-band emission was correlated with the star luminosity, as illustrated on Fig. 2 (left). From this correlation they have demonstrated that the near infrared excess of such stars was – at the exception of the most luminous ones – arising from the thermal emission of the inner part of the dusty circumstellar disk, located at the dust sublimation radius, assuming that the dust is in equilibrium with the radiation field (ie $R_{sub} \sim 0.5\sqrt{\frac{Q_{abs}(T_*)}{Q_{abs}(T_{sub})}}\left(\frac{T_*}{T_{sub}}\right)^2 R_*$,where T_{sub} is the dust sublimation temperature, roughly $T \sim 1500$K for silicates). If this scenario works well for Herbig Ae stars and late Be, it however fails to interpret the size of the infrared excess emission region for the early Be, the inner rim being too close to the star regarding their high luminosity. In this case, one likely interpretation is that the gas inside the dust sublimation radius is optically thick to the stellar radiation, hence shielding a fraction of the stellar light and allowing the dusty inner rim to move closer to the star, as sketched on Fig. 2 (right).

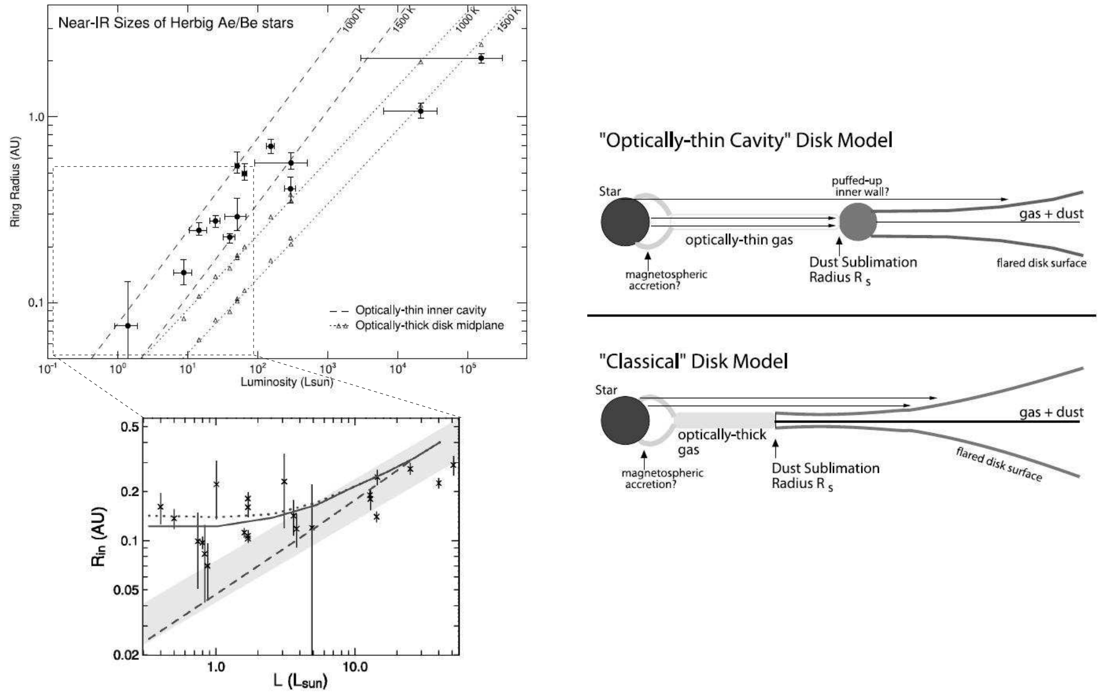

FIGURE 2. Left: K-band interferometric size-luminosity relationship for intermediate [6] and low [8] mass young stars. We can see in the bottom plot that for the T Tauri regime, considering the thermal emission only (dashed line) does not reproduce the correlation whereas taking into account both the thermal and scattered light emission with the same disk model (solid line) does. Right: schematic representation of the inner environment of young stars, with respectively optically thin (top) and optically thick (bottom) material within the dust sublimation radius (from [6]).

T Tauri stars: a strong contribution of the scattered light

Together with the last improvements of interferometers in terms of sensitivity, it is only recently that the same kind of study could have been performed on the less luminous T Tauri stars. And the results that have been obtained were somewhat surprising, the size of the NIR emission being *larger* than predicted [9, 10, 11]. Many hypothesis were invoked such as lower sublimation temperature $T_{sub} \sim 1000$K, fast dissipation of the inner disk, magnetospheric radii bigger than dust sublimation ones hence defining the location of the inner rim... until Pinte et al. [8] have shown that as long as the luminosity of the star decreases, the contribution of the scattered light, in addition to that of the thermal emission, could not neglected anymore. As a consequence, as shown inf Fig. 2, these authors have convincingly demonstrated that the model of the inner disk located at the dust sublimation radius was holding for the T Tauri regime as well, and that no alternative scenario was required as long as the radiative transfer in the disk was thoroughly studied (thermal + scattered light).

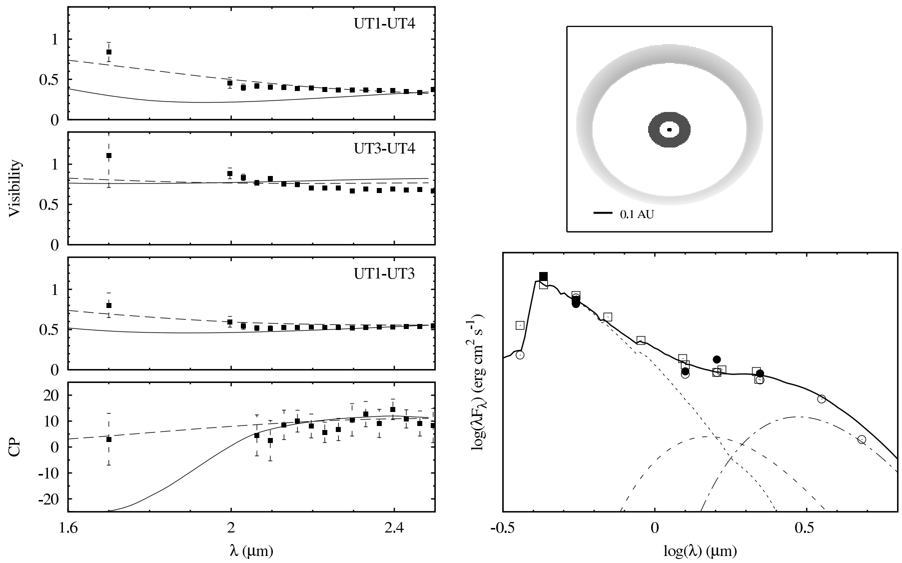

FIGURE 3. Left: H and K band visibilities and closure phases of MWC758, from Isella et al. [12]. The solid line represents the model of dust inner rim only, the dashed one being the unresolved point + dust model as shown in the right top corner. Below is shown the SED, well reproduced by the star (dotted line) + unresolved point (dashed line) + dust (dash-dotted line) model.

RESOLVING THE HOT GAS CONTINUUM EMISSION

Though dust is mostly dominating the near infrared continuum emission of young stars, there are some cases, especially for stars where the accretion rate is high enough – roughly $> 10^{-7} M_{\odot}$/yr – where the contribution of the dust-free hot gaseous component to the NIR excess is not negligible. Since the dust-free gas is located between the star and the dust sublimation radius, we expect the region of emission to be *hotter* and *more compact* than that of the dusty inner rim. As a consequence, going towards shorter wavelengths or longer baselines appear to be well suited strategies to probe this region.

In this framework, Isella et al. [12] have observed the Herbig Ae star MWC 758 with the AMBER instrument on the VLTI, both in the H and K bands. They have shown that, if the K band observations alone are well interpreted by the classical dusty puffed-up inner rim ($T_{sub} = 1400$K, $R_{in} = 0.34$AU), it fails to reproduce the H band observations for which the emission is less resolved than expected by this model. Furthermore, with this single model, the SED can be not fitted successfully, showing a lack of energy in the H band. Conversely, by adding to the model the presence of an unresolved hotter component (of $T_g = 2500$K), they managed to reproduce both the H and K bands measurements jointly. Note that this changes slightly the parameters of the dusty rim ($T_{sub} = 1300$K, $R_{in} = 0.40$AU). What was then the physical interpretation for this unresolved component? Given the temperature and the size (≤ 0.1AU) of the emission region, it is likely that AMBER has directly probed the hot gas accreting close to to the star. And indeed, models of accreting gas developed by Muzerolle et al. [13] (assuming an accretion rate of $\sim 2.10^{-7} M_{\odot}/yr$ from the star's Brγ luminosity), allow as well to satisfactory fit the shape of the SED by filling the lack of energy in the H band (see Fig.

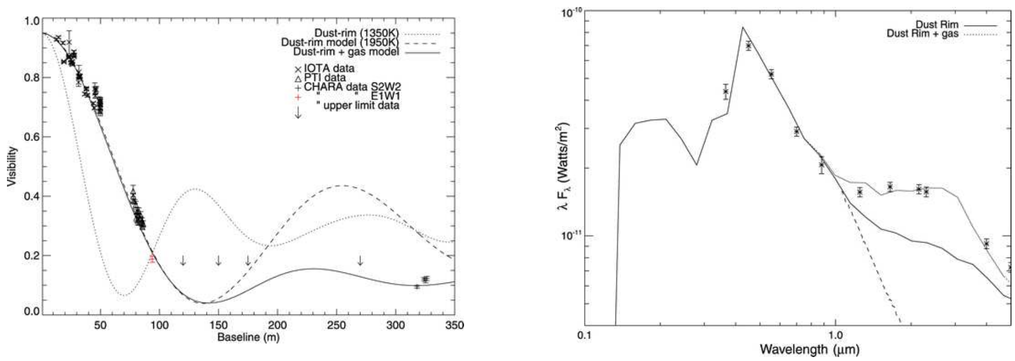

FIGURE 4. Left: Visibility of AB Aur as a function of the projected baseline (from Tannirkulam et al. [15]). If the dust rim model alone succeeds in fitting the shorter baselines up to 100m, the interferometric data at 300m require the presence of a compacter component inside the sublimation radius, interpreted as arising from the hot dust-free inner gas, this extra component being responsible for 65% of the K-band excess, as shown in the SED (right).

3), hence reinforcing this interpretation.

Somewhat similar strategy was used by Eisner et al. [14] who observed different Herbig Ae/Be stars with the KecK interferometer, using moderate spectral dispersion (R=25) within the K-band. They hence have found that for several stars of their sample, single-temperature ring could not reproduce the data well, and that models incorporating radial temperature gradients or two rings should be preferred, supporting the view that the near-IR emission of Herbig Ae/Be sources can arise from both hot circumstellar dust and gas. For example, the interferometric data of AB Aur require the presence of one dust inner rim together with a more compact and hotter component ($T \sim 2000$K) interpreted as coming from the hot dust-free inner gas. And as a matter of fact, this scenario was confirm by Tannirkulam et al. [15] who observed the same star with the very long baselines (300m) of the CHARA interferometer, hence probing smaller emission region and showing the need of adding smooth hot ($T > 1900$K) emission inside the dust inner rim, contributing to 65% of the K-band excess, as summarized in Fig. 4.

THE ORIGIN OF NIR EMISSION LINES

One major achievement in interferometry in the past years is the capacity of spectrally dispersed the interferogram with resolution high enough (AMBER/VLTI: R=1500, and very recently KecKI: R=1700, that is some 100km/s) to spatially resolve the lines emission regions together with that of the continuum, that is to directly probe the gas which constitutes 99% of the mass of the circumstellar matter.

The origin of Brγ emission in Herbig Ae/Be stars: probing the accretion/ejection phenomena:

Among all the NIR emission lines that are seen in young stars, the atomic transition of the hydrogen Brγ is the most observed in spectro-interferometry for it is the brightest and can therefore be studied with rather good signal to noise ratio. However, since (i) the number of measurements remains poor in classical interferometric observations (two or 3 baselines simultaneously) and (ii) the spectral resolution is not high enough to *spectrally* resolve the line, the interferometric measurements must be, so far, interpreted in terms of simple geometrical models. The analysis is done as follows: measure the size of the emitting region for both the emission line and the surrounding continuum, then compare their relative size to put some strong constraints on the physical mechanisms at the origin of the emission line. Typically, as described in introduction, two main scenarios are in balance:

- *magnetospheric accretion:* If the line is emitted in accreting columns of gas, then the region of emission lies roughly between the star and the corotation radius, that is *the line emission region is much more compact than that of the continuum* which comes from the dust sublimation radius, as described in previous Section.
- *outflowing winds/jets:* At the contrary, for such scenario, we expect the *line emitting region to be of the same size or bigger than that of the continumm.*

Using the AMBER instrument, Malbet et al. [16], Tatulli et al. [17], Kraus et al. [5] have observed a sample of Herbig Ae/Be stars that displayed strong Brγ lines and have performed for each star the geometrical analysis described above, that is by comparing the size of the line emitting region with respect to that of the continuum, as illustrated in Fig. 5. As a result, if for two stars (HD98922, MWC480) the interferometric measurements were compatible with the magnetospheric-accretion for the origin of their Brγ emission, the wind scenario was favored for four of them (MWC275, MWC297, V921Sco, HD104237). Taken statistically, these results are quite interesting to analyze: at the contrary of T Tauri stars for which the direct correlation between accretion and Brγ emission seems well established, in Herbig Ae/Be stars we are mostly probing outflows phenomena from Brγ emission, this latter being probably in this case an indirect tracer of accretion through accretion-driven mass loss.

The origin of CO overtone emission: probing the hot molecular gas

Whereas Brγ is a good tracer of whether magnetospheric accretion or outflowing winds, some other lines such as the CO overtone emission at 2.3μm are also of great interest to directly probe the hot rotating gas. One problem however is that only a few young stars display strong enough CO lines to be observed with spectro-interferometry. 51 Oph is one these stars [18, 19], and Tatulli et al. [20] have recently presented the first interferometric observations of this young star around the CO overtone emission, using the AMBER instrument with the resolution of 1500. They have shown that: (i) the hot CO emission was resolved, located at a distance of 0.15AU from the star, thus in

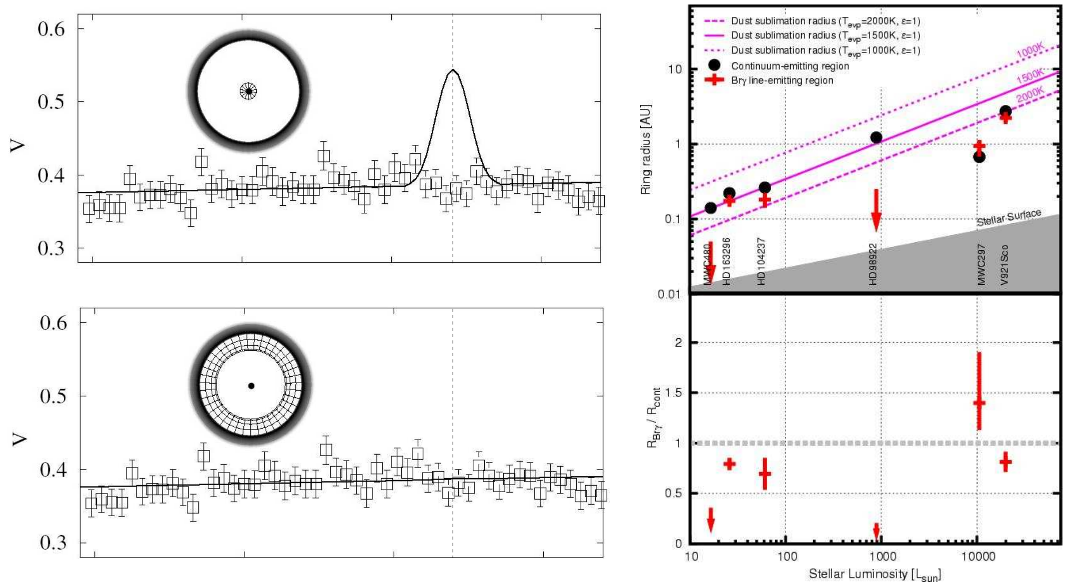

FIGURE 5. Left: visibility around the Brγ line at 2.16μm (indicated with a dashed line) of HD104237 and superimposed magnetospheric-accretion (up) and wind (down) models, from Tatulli et al. (2007). Size of the Brγ region for 6 Herbig Ae/Be stars as a function of the star's luminosity, from Kraus et al. (2008).

agreement with the scenario in which the CO is emitted from the first AU of a rotating gaseous disk [18], (ii) the two first bandheads are arising from the same emitting region, and (iii) the adjacent continuum is located at a distance of 0.25AU, that is too close to the star compared to the location of the sublimation radius, suggesting that the stellar light is shielded by the optically thick gas hence moving the sublimation radius closer to the star, and/or that the hot gas inside the dust sublimation radius significantly contributes to the observed 2 μm emission (free-free emission).

PROSPECTS AND EXPECTED DEVELOPMENTS

Although optical interferometry has undergone significant improvements in the past few years that have enabled to increase our understanding of the inner part of protoplanetary disks on a growing sample of young stars, some instrumental limitations yet prevent to unambiguously draw a comprehensive picture of their environment. Strong efforts are now undertaken to improve the capabilities of current and future interferometers, which can be summarized around three main axes:

- *increasing the flux sensitivity:* thanks to dedicated fringe tracking/phase referencing devices, a better sensitivity will enable to observe (i) lower mass sources and (ii) fainter NIR emission lines which will be fully complementary of the Brγ line to characterize the rotating gas and the accretion/ejection phenomena (CO, Fe, Pa β,...).
- *going to higher spectral resolution:* a better sensitivity will also allow to use spectrographs performing higher resolution, with conserving enough flux in each spectral channel. Typically, a spectral resolution of $R > 8000$ (i.e. a few tens of km/s) will enable to spatially and *spectrally* resolve the emission lines, and will as well provide the veloc-

ity maps of their emitting regions, putting to a test e.g. the rotation at the base of the jets [21], or the keplerian nature of the rotating gas.
- *developing the imaging capabilities:* an increased number of telescopes simultaneously recombined (typically 6 or more [22]) is indeed mandatory to obtain enough measurements to obtain snapshot (i.e. in a few nights of observations at most) images of the inner environment of young stars, allowing to (i) set free from simple geometrical model-dependant analysis of the physical mechanisms at play and (ii) perform a temporal follow up of sources in adequacy with the dynamics at stake within the first AU of the protoplanetary disks.

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